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By John W. Kopp

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

atm	atmosphere	in^3	cubic inch
°C	degree Celsius	in^3/s	cubic inch per second
ft	foot	K	Kelvin
ft/s	foot per second	lb	pound
g	gram	mm	millimeter
g/cm^3	gram per cubic centimeter	ms	millisecond
in	inch	ms/ft	millisecond per foot

STEMMING EJECTION AND BURDEN MOVEMENTS FROM SMALL BOREHOLE BLASTS

By John W. Kopp[1]

ABSTRACT

Stemming is used in blasting operations to help contain explosive gases as long as possible. Stemming can reduce airblast, improve fragmentation, and reduce the chances of hot explosive gases igniting methane and dust explosions in underground mines. Stemming is required in underground coal mines but is generally not used in underground metal and nonmetal mines. Some underground metal and nonmetal mines are classified as gassy and can require special blasting procedures such as the use of stemming to insure the safety of miners.

The types and amounts of stemming material that are desirable in underground metal and nonmetal mine blasting to ensure good or improved fragmentation while containing the hot gases are largely unknown. This Bureau of Mines research examined the effectiveness of differing lengths of stemming by measuring stemming ejection times as related to burden movement. With properly stemmed blasts, stemming is contained until some burden movement has occurred.

Test blasts at two surface limestone quarries were evaluated using high-speed photography. For the conditions of these tests, a stemming length of at least 26 charge diameters was found to prevent premature stemming ejection. In tests with stemming lengths of 16 charge diameters, the stemming was effective but there was early venting of hot gases through fractures in the rock. Further testing with other rock types, hole diameters, explosive types, and stemming materials as they affect incendivity is recommended.

[1]Mining engineer, Twin Cities Research Center, Bureau of Mines, Minneapolis, MN.

INTRODUCTION

Methane emissions in underground mines can present hazards especially when ignition sources such as explosives are present. The problems associated with blasting in underground coal mines have been dealt with by use of permissible explosives and permissible procedures for their use. However, methane also occurs in some noncoal underground mines, particularly oil shale, trona, salt, potash, copper, limestone, and uranium. At present, blasting operations in such mines are conducted with a variance from Mine Safety and Health Administration (MSHA) regulations depending on the source of methane, associated ore body, and the method of mining. Conventional explosives and blasting agents, rather than permissible explosives, are normally used for both practical and economic reasons.

A recent Bureau contract[2] examined blasting practices in gassy noncoal mines. Most of these operations use conventional explosives in standard underground blasting practices. Safety is sometimes insured by evacuating all personnel to the surface during the blast. However, this is often not practical for large mines utilizing mining methods such as room-and-pillar. Some mines require 20 or more blasts per day involving large amounts of explosives. In order to maintain production, blasts must be scheduled while personnel are working in the mine.

Workman made a number of recommendations for blasting underground with personnel present in the mine. Important among these was use of stemming to contain the hot gases and flame of the explosive in the borehole until expansion of the burden sufficiently cooled the gases to prevent ignition of methane. Workman made some predictions of the stemming behavior but this was based only on a simple mathematical model. He recommended that his calculations be confirmed by field studies.

Stemming is not normally used in noncoal mine underground blasting as its use adds another step to the blasting operation and increases expense. There can be advantages to the use of stemming, however, in terms of improved blasting results. Early laboratory tests by Snelling (1)[3] demonstrated that high explosives were more efficient with the use of stemming than without. Later tests by the Bureau (2-7) made in hard-rock drift rounds also showed that stemming increased the efficiency of the explosives used. Sand was the most effective stemming material of those studied, although clay worked well also.

Stemming is a requirement for blasting with permissible explosives in coal mines. The most common stemming material is tubes of fire clay. In the 1950's and 1960's, other material was tested by the Bureau (8-9) including water bags and special stemming devices. Water bags for stemming in coal mines were originally developed in Europe in the 1950's (10-11). A great deal of work on various stemming materials was done in Europe at this time and is reported by Hofmeister (12).

Recent stemming research studied the physical mechanisms involved and the function of stemming during the blast. Konya (13) related the minimum amount of stemming required to retain all blast products to the pressures developed in the blasthole. This work was done for the purpose of controlling airblast.

The study of stemming for control of methane ignitions has been incidental to the development of permissible explosives in underground coal mining. This coal mine research has thus been limited to small charges of relatively low-energy explosives. No adequate studies have been conducted of the use of stemming to prevent methane ignitions in large blast rounds using conventional explosives.

This Bureau of Mines study was conducted to measure the retention time of various lengths of stemming in the borehole during normal blasting, and to relate stemming retention time to the

[2]Contract J0215031; Bauer, Calder, & Workman, Inc.

[3]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

burden movement caused by the expanding gases of the explosive. Tests were conducted at two surface limestone quarries, which allowed careful control of the test blast design variables and adequate lighting for high-speed photography. Twelve single vertical hole test blasts (1-1/2-in-diameter) were detonated in a factorial experiment with two types of stemming, two explosives, and three lengths of stemming. Additional blasts were monitored using 1-7/8-in-diameter horizontal holes drilled into the base of a highwall and also with 6-in-diameter vertical holes drilled into the quarry floor.

ACKNOWLEDGMENTS

The author is grateful for the assistance of the J. L. Shiely Co. for use of its Carl Larsen quarry. The author also wishes to thank Atlas Powder Co. and Sandia National Laboratories for their cooperation with the large-scale test shots.

EXPERIMENTAL DESIGN AND PROCEDURE

The primary experimental method chosen for studying stemming behavior was high-speed cinematography. A series of laboratory scale tests were conducted to test camera and film analysis procedures and to assess other methods of observing stemming movement.

The laboratory tests were conducted in concrete blocks in a blasting shelter, which limited the maximum charge weight to 10 g. Drill holes of 1/2-in diameter were used with depths varied from 5 to 17 in. A PETN-based detonating cord was used as the explosive with charge weights ranging from 0.1 to 5 g plus the blasting cap. These initial tests used silica sand for stemming material. Analysis of these early test films showed that stemming movement could be adequately monitored. In addition, movement of burden could also be calculated and compared with stemming movement. Set up of the camera and procedures used to analyze the films are similar to those discussed by Blair (14).

Field experiments were filmed with two cameras, a 16-mm rotating prism camera capable of speeds up to 11,000 frames per second and a 16-mm registering pin camera with filming speeds up to 500 frames per second. The registering pin camera has better resolution than the rotating prism camera and thus provides a much clearer picture.

The time of detonation of the explosive was recorded on film with Nonel[4] shock tubing. A known length of shock tubing was attached to the explosive charge and passed through the stemming to the surface and was coiled to allow the flash to be recorded on film. Detonation of the explosive will initiate the tubing, which detonates at 6,000 ft/s. Thus the time of detonation is determined by noting the flash of the coiled tubing on the film and calculating the time required for the detonation to reach the surface.

Full-scale field tests were performed at a surface limestone quarry in order to eliminate lighting problems when filming with the high-speed cameras. Twelve cratering shots were detonated for a factorial experiment to test two types of stemming material at three lengths of stemming and with two explosive types.

A high-energy explosive and a relatively low-energy explosive were used for this series of tests. The low energy explosive was chosen to produce results similar to ANFO. Both explosives were in 1-1/4-in-diameter cartridges. Enough explosive was used in each test to make a charge 16 in long. The volume of explosive was not varied for this test series. Properties of the explosives used are shown in table 1.

The blastholes were 1-1/2-in diameter and varied from 36 to 72 in deep. The holes were drilled vertically in a limestone quarry floor. This represents the worst case for blasting efficiency,

[4]Reference to specific products does not imply endorsement by the Bureau of Mines.

TABLE 1. - Properties of explosives used in the test series

Explosive type	Density, g/cm^3	Detonation velocity, ft/s	Relative bulk strength[1]	Explosive temperature, K	Borehole pressure, atm
High energy............	1.16	15,000	148	3,000	30,000
Low energy.............	1.07	10,500	115	2,870	19,000
Permissible............	1.18	16,500	120	2,450	37,000
Emulsion...............	1.25	18,000	145	3,000	50,000

[1]ANFO = 100.

allowing relief in only one direction, upward. Thus, stemming should be ejected more readily than in a normal blast design.

The stemming material consisted of crushed limestone in one of two sizes. The material was either drill cuttings screened to less than minus 10 Tyler series mesh size (0.0661 in), or limestone gravel between 3/8- and 3/16-in size. The stemming material was added above the explosive and filled the hole to the collar. Table 2 shows stemming length and type, explosive type, and assignment of shot numbers. The stemming was lightly tamped and had a density of about 1.5 g/cm^3.

Additional tests were done on larger diameter blastholes at another limestone quarry in cooperation with Sandia National Laboratories and Atlas Powder Co. Two types of blasting were involved. The first type of blast used 1-7/8-in-diameter horizontal blastholes, 5 ft long, and drilled into the base of the highwall. Three 12-in cartridges of a permissible explosive were loaded into each hole, followed by 2 ft of clay "dummies" as used in coal mine blasting. The shot was monitored with a high-speed camera running at 500 frames per second. The time of detonation was recorded on film by use of Nonel shock tubing.

TABLE 2. - Experimental design and assignment of test numbers

Length of stemming..in..	20	32	56
Fine drill cuttings:			
High-energy explosive.	S-3	S-2	S-11
Low-energy explosive..	S-6	S-12	S-1
Coarse crushed stone:			
High-energy explosive.	S-4	S-8	S-10
Low-energy explosive..	S-5	S-7	S-9

The second type of blast was a shot with three vertical 6-in-diameter holes 15 ft deep. An explosive charge of 60 lb was placed in the bottom 6 ft of each hole. The upper 9-ft-length was stemmed with 3/8- to 1-in size crushed limestone gravel. Each hole was marked with shock tubing to indicate the time of detonation.

The second test also included Sandia's shorted length indication by frequency of electrical resonance (SLIFER) detonation velocity detection system in each hole (15). This system measures the rate of crushing or ionization of a coaxial cable buried in a blasthole by measuring electronically the length of cable remaining intact as a function of time as the detonation front proceeds up the explosive column. The stemming material is also crushed or compacted, and this rate can be measured with the SLIFER system.

RESULTS

CRATER TESTS WITH 1-1/2-IN-DIAMETER BLASTHOLES

Twelve cratering tests were conducted according to the factorial design of table 2. All shots were monitored with two high-speed cameras, one running at 500 frames per second and the other at 1,000 to 3,000 frames per second. Analysis of the films showed that stemming was usually ejected from the shallow holes. Results of this analysis are shown in table 3. With stemming lengths of 20 in or more, the stemming material was completely contained or it took at least 8.8 ms for stemming ejection to occur.

TABLE 3. - Observed ejection times of 20-in stemming material,[1] milliseconds

Stemming and explosive type	
Fine drill cuttings:	
High-energy explosive........	13
Low-energy explosive.........	32
Coarse crushed stone:	
High-energy explosive........	8.8
Low-energy explosive.........	Retained

[1]Stemming materials of 32- and 50- to 60-in lengths were retained.

When stemming is retained it has done its job in terms of confining the hot explosive gases. However, when stemming is ejected, further analysis is required to determine if an adequate length of stemming has been used.

Further analysis of the films allowed one to observe the motion of burden. Not only can velocities of various parts of the burden be calculated, but an estimate of the increased burden volume caused by the expanding gases can be made. Figure 1 shows stemming and burden movement for shot S-3, which was a test with 20 in of fine stemming that resulted in a stemming ejection time of 13 ms. Initial movement of the stemming is obscured by dust caused by venting through cracks in the burden. The initial velocity of the stemming was calculated to be 190 ft/s. The burden velocity was calculated to be 27 ft/s. The increase in burden volume was calculated by assuming the burden movement to be in the shape of a cone and measuring this increase on figure 1. It is apparent from the figure that the burden movement is closely approximated by a cone. The rate of volume increase was found to be 600,000 in^3/s.

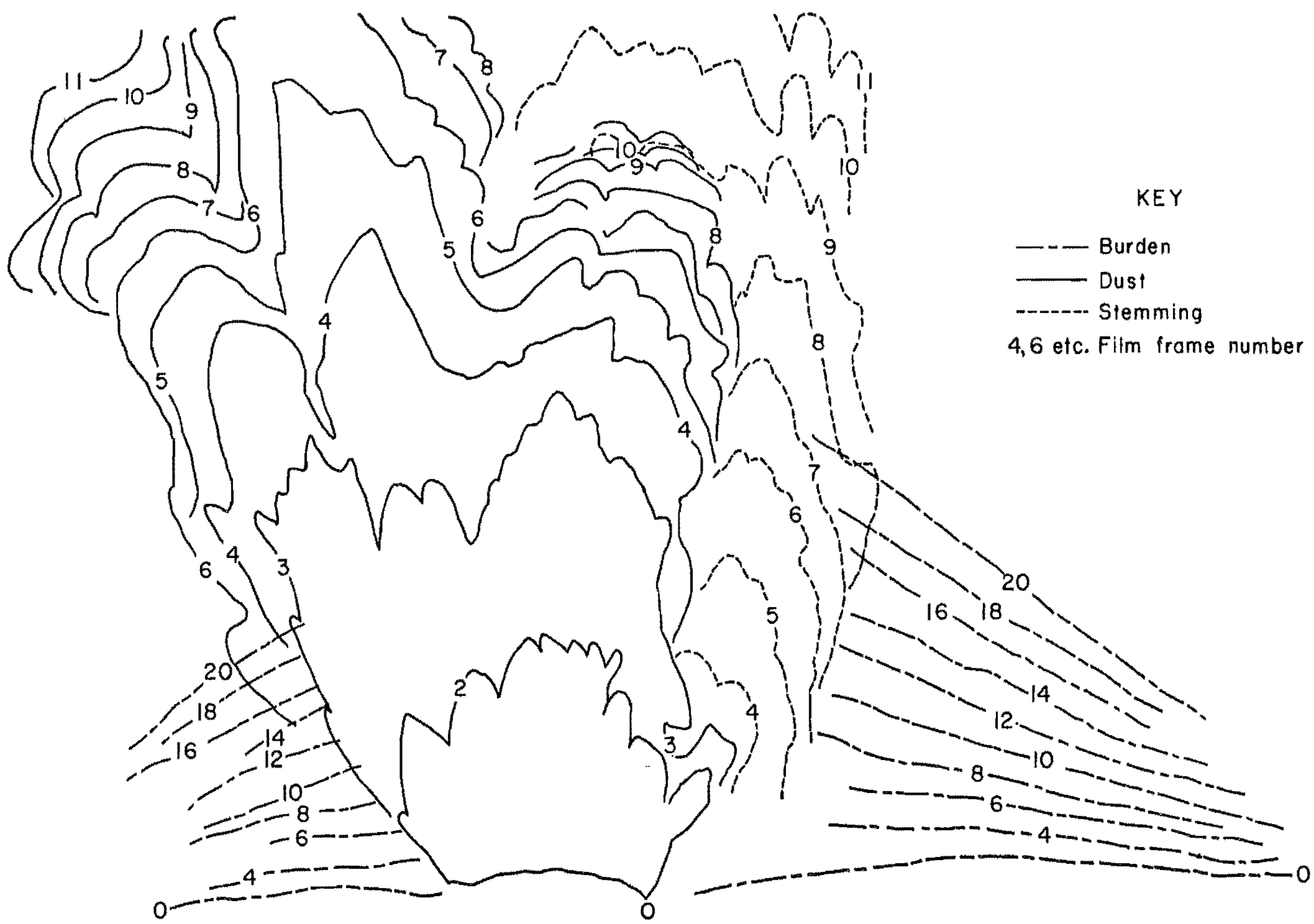

FIGURE 1.—Stemming and burden movements of shot S-3.

A plot of stemming movement and burden expansion versus time elapsed from initiation of detonation is shown in figure 2 for shot S-3. It is apparent from figure 2 that considerable burden movement occurred before the stemming was completely ejected after 13 ms. In this case, some cooling of the hot explosive gases has occurred due to volume expansion as the gasses work their way into the fractured burden region.

An estimate of the amount of explosive gas cooling can be obtained as follows. The thermodynamics of the expansion are assumed to be adiabatic. The expansion is rapid and allows little time for heat to be exchanged between the gases and the surrounding rock. From the first law of thermodynamics it can be shown that temperature and volume of the gas are related as follows:

$$T_1^{\left|\frac{1}{\gamma-1}\right|} V_1 = T_2^{\left|\frac{1}{\gamma-1}\right|} V_2, \qquad (1)$$

which on rearranging becomes

$$T_2 = \left|\frac{V_1}{V_2}\right|^{\gamma-1} T_1, \qquad (2)$$

where T_1 and T_2 are the initial and final temperatures, V_1 and V_2 are the initial and final volumes, and γ is the ratio of the heat capacities of the expanding gases. The actual value of γ depends on the molecular structure of the gases involved. Most of the gas products of the explosives used are diatomic and polyatomic gases—nitrogen, carbon dioxide, and water vapor. The average value of γ for these gases is approximately 1.3.

The equation describing the gas temperature line on figure 2 becomes

$$T = \left|\frac{V_1}{V}\right|^{0.3} T_1, \qquad (3)$$

where V_1 and T_1 are the initial volume and temperature of the explosive at detonation, V is the increase in volume, and T is the temperature at that value of volume. It is now assumed that the gas

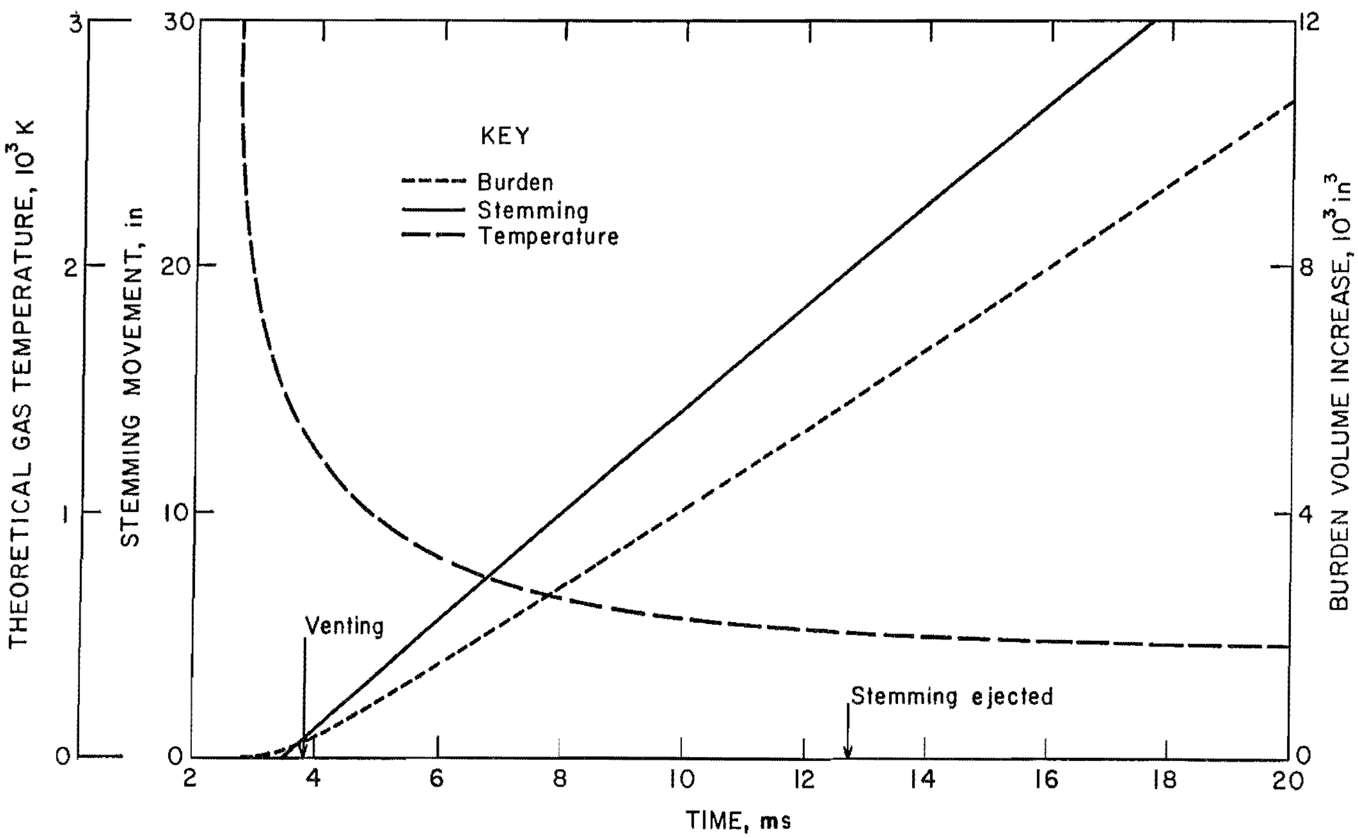

FIGURE 2.—Relative movements of stemming and burden for shot S-3 and associated gas temperature.

expands into all of the new volume created by the expanding burden. The expanding gases may not fill all of the new spaces created by fracturing of the burden. However, no allowance is made for expansion of the gases into existing voids or for porosity of the rock. The estimated temperature is thus an approximation but provides some insight into the phenomena involved.

Figure 2 also shows the predicted gas temperature decrease based on the use of equation 3 and the burden volume increase as determined from analysis of high-speed films. The stemming remained in the borehole for 13 ms at which time the gas temperature is estimated to have cooled from the detonation temperature of 3,000 K (2,727° C) to 550 K (277° C), which would be sufficient to prevent ignition of a methane-air mixture. The ignition temperature of methane is 905 K.

However, from figure 1, it is evident that venting, probably through a major fracture, occurred before expulsion of the stemming. This occurs at 3.8 ms after initiation. Figure 2 shows that the explosive gases would have cooled to 1,300 K after 3.8 ms, not sufficient cooling to prevent methane ignition. Because of previous blasting, a significant fracture pattern existed in this limestone rock.

A similar analysis was performed for shots S-4 and S-6. Results are presented in figures 3 and 4. Figure 3 presents the analysis of shot S-4 where 20 in of coarse stemming was ejected using the high-energy explosive. At the time of stemming expulsion at 8.8 ms, the explosive gasses were estimated to have cooled to 650 K, within a safe temperature range. However, venting of dust and smoke was observed at 3.5 ms after initiation. From figure 3, the estimated temperature of the gases would be 980 K, above the safe limit. Again, the venting probably occurred through existing fractures in the rock. This shot, and the previously discussed shot, used a high-energy explosive but different stemming size. The finer material held longer.

Shot S-6 had 20 in of fine stemming and the lower volume-energy explosive. Stemming was ejected from shot S-6, but not

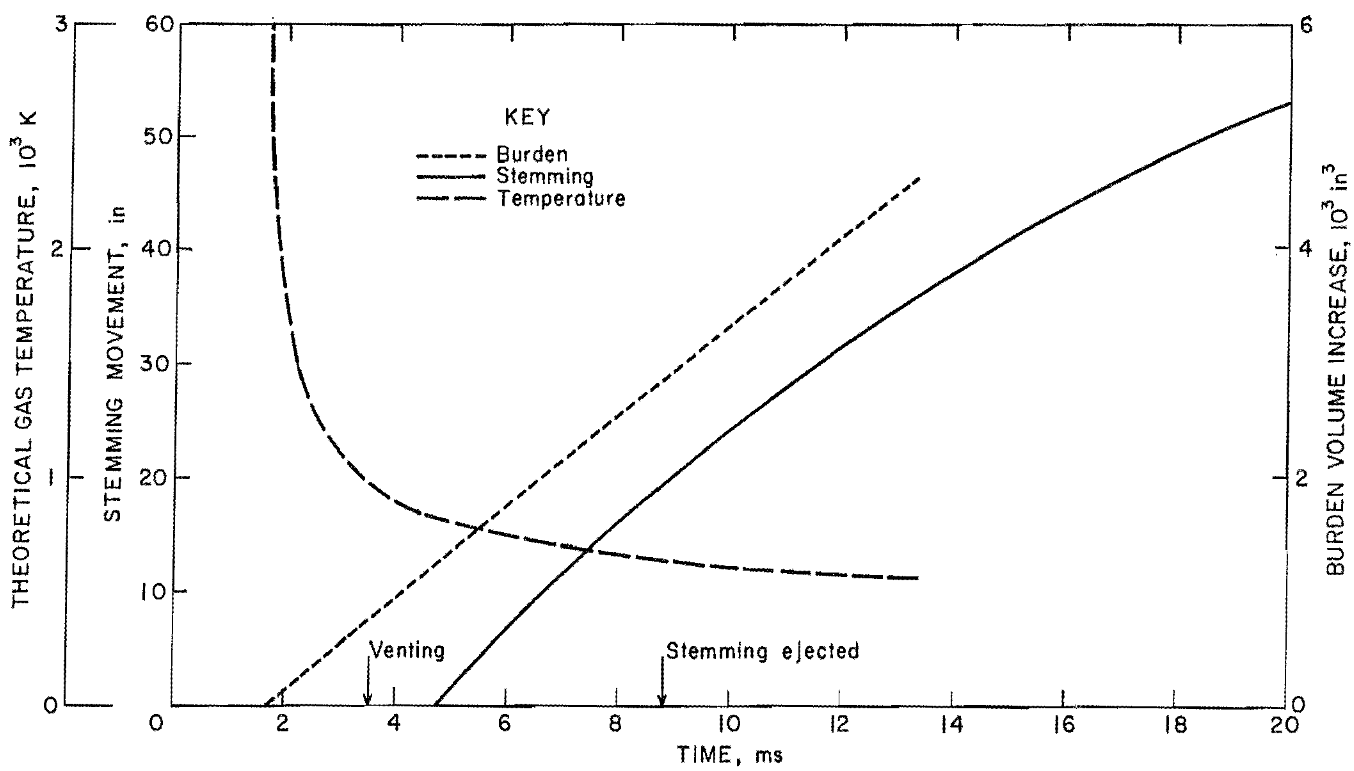

FIGURE 3.—Relative movements of stemming and burden for shot S-4 and associated gas temperature.

as soon as with the higher energy explosive (fig. 4). The time for ejection was 32 ms and the estimated gas temperature at that time was 625 K. Venting of smoke or dust was also observed starting at 4.8 ms after initiation. From figure 4, the estimated gas temperature at the beginning of venting is about 1,300 K, high enough for a potential methane ignition.

Four shots were fired with 32 in of stemming in each hole. The stemming remained intact for all these shots. The film analysis did not show any stemming movement. Burden movement was slower than in the previous shallower shots. With the exception of shot S-12, no venting of smoke or dust occurred. Also, a rubble zone of broken material was left at the surface of each hole. The zone was about 2 ft in diameter for three of these shots. The shots with 20 in of stemming left a larger rubble zone on the surface, 2 to 5 ft in diameter. Thus, the explosive was placed sufficiently close to the surface with 32 in of stemming to allow fragmentation of the burden.

The final four shots of this series used stemming lengths of 50 to 60 in. No stemming movement was detected for any of these shots. Burden movements were also smaller than for the previous shots. Figure 5 shows a comparison between burden velocities and the length of stemming used in each hole. The type of explosive used made a difference in burden velocity only at the two shortest stemming lengths. Differences caused by stemming type were inconclusive.

In this crater test series with 1-1/4-in charges in 1-1/2-in-diameter blastholes, it was found that stemming

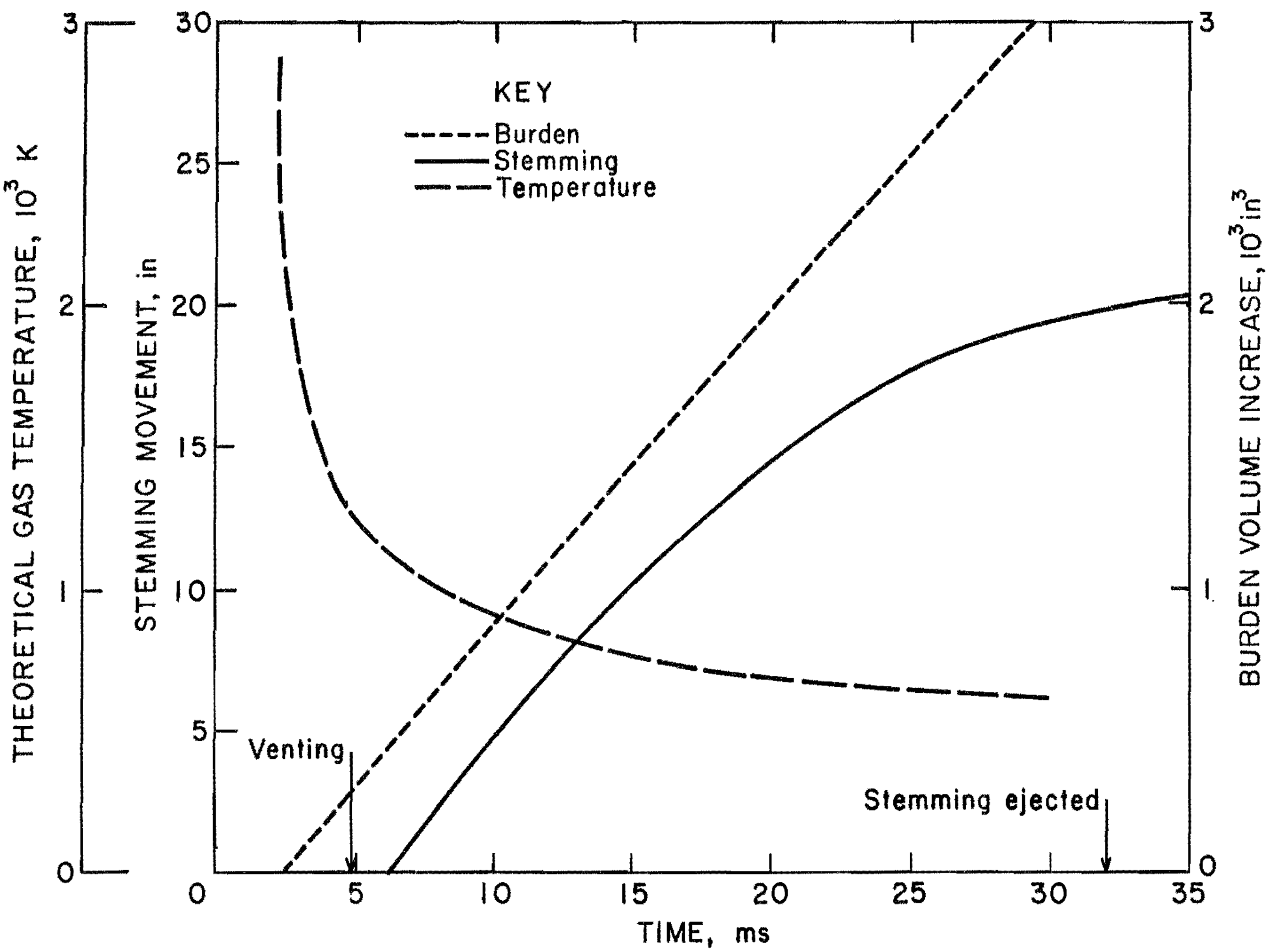

FIGURE 4.—Relative movements of stemming and burden for shot S-6 and associated gas temperature.

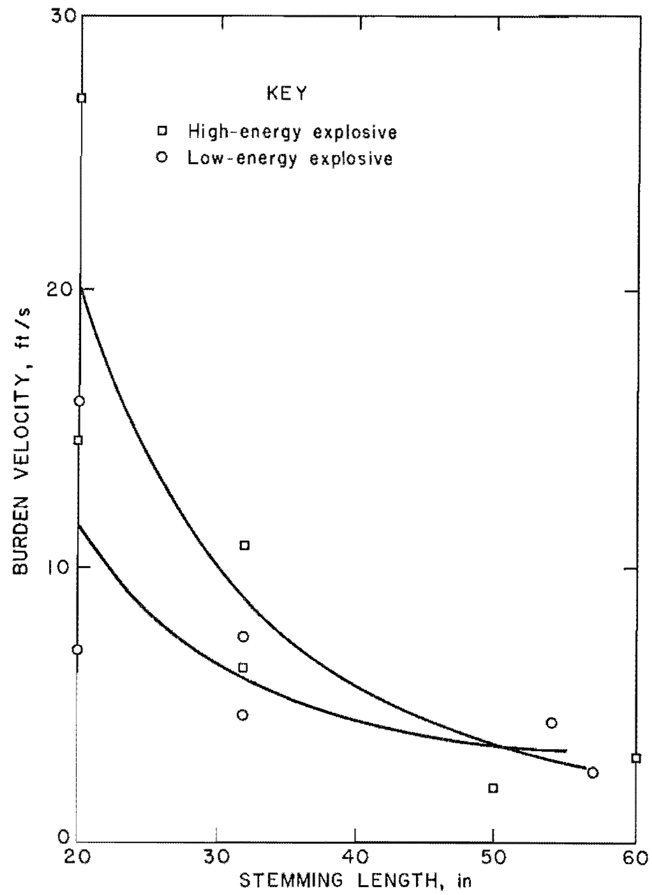

FIGURE 5.—Observed burden velocities versus length of stemming for 1-1/2-in-diameter shot series.

was retained in all cases with stemming regions of 32 in or greater. When 20 in of stemming was used, there was stemming ejection in three of the tests after 8.8 ms or more but venting of gases through fractures occurred before 8.8 ms. Estimates of explosive gas cooling associated with volume increases as the explosive gases expand into the fractured burden were made. The estimated explosive gas cooling for the three tests where stemming ejection occurred was sufficient to prevent ignition of methane in the time required for stemming ejection (8.8 ms) but was insufficient at the time when venting of gases through fractures occurred. There was no premature venting of gases with a 32-in stemming region. It is concluded then that for the conditions of these tests, a stemming length to charge diameter ratio of 26 (32 in of stemming) was adequate to prevent ignition of methane. However, a stemming length of 16 charge diameters (20 in of stemming) could have resulted in methane ignitions because of early venting of hot gases through fractures in the limestone rock.

TABLE 4. - Results of horizontal hole shots using permissible explosives and stemming

	Stemming		Burden	
	Ejection time, ms	Velocity, ft/s	1st movement, ms	Velocity, ft/s
H-1	4.0	1,800	4.5	62
H-2	4.0	1,600	2	22
H-3	3.4	2,100	NO	NO

NO Not observed.

OTHER CRATER TESTS

Shots with other borehole diameters were also studied. Three horizontal holes using 3 lb of permissible explosive and 2 ft of clay dummies for stemming in 1-7/8-in-diameter holes were filmed. Results for these tests in a limestone surface quarry are shown in table 4.

An additional shot was fired without stemming. Flame was observed exiting the borehole at 6,000 ft/s velocity and extended over 2 ft from the collar. The flame appeared at the time of initiation, thus, stemming retarded the flame in the stemmed shots.

A burden and temperature graph is shown for shot H-3 (fig. 6). In this case, volume expansion is only the increase in the borehole volume caused by expulsion of the stemming, as burden movement was not detected in analysis of the films. Expulsion of stemming occurs at about 3.4 ms, at which time the gas temperature is estimated at 1,900 K. All horizontal shots in this series gave similar results.

A vertical cratering shot, V-1,[5] using an emulsion in three 6-in-diameter holes was also monitored with high-speed cinematography. Each hole was 15 ft deep, with 6 ft of explosive and 9 ft of stemming. The blastholes were sufficiently far apart so that they did not interact

[5]Sandia Laboratories shot 8-S (15).

and could be considered as three separate shots. Holes 1 and 2 in this test did not have expulsion of stemming. Hole 3 had stemming movement but not complete expulsion. Stemming and burden movements for hole 3 are shown in figures 7 and 8. The portion moving near the collar in figure 7 is the stemming material and had an initial velocity of 38 ft/s. The burden had a velocity of 27 ft/s. Hole 1 behaved in a similar way, with a burden velocity of 24 ft/s and stemming moving with the burden. Hole 2 showed no burden movement. This was probably because of escape of the explosive gases through fractures in the rock. No signs of escaping gases were evident in the films, however.

COMPARISON OF ALL CRATER DATA

Comparisons were made between these larger holes and the 1-1/2-in-diameter cratering shots. In order to make fair comparisons of shots with differing hole diameters, the stemming lengths and hole diameters must be normalized. Two methods were used. The first was to simply divide the stemming length by the charge diameter. The maximum burden velocity was compared in this way. The results compared best when plotted logarithmically (fig. 9). Figure 9 shows that the burden velocity data from the 1-1/2-in-diameter tests, the horizontal hole tests, and the 6-in-diameter crater shots can be grouped using a stemming length to charge diameter ratio normalization.

The second method used to compare data from different hole sizes was to plot the rate of burden volume expansion versus the scaled depth of burial of the explosive charge. The rate of this volume expansion was normalized to account for differing amounts of explosive by dividing burden volume expansion by the volume of the explosives in the borehole. This parameter was found to correlate well with the scaled depth of burial of each shot. Scaled depth of burial was found by dividing the depth in feet to the center of the top of the explosive charge by the cube root of the weight in pounds of the top eight borehole diameters of explosive charge (16). Results of this are shown in figure 10. From figures 9 and 10 it is apparent that the larger hole sizes fall within the trend of the data and thus the scale factors discussed are appropriate.

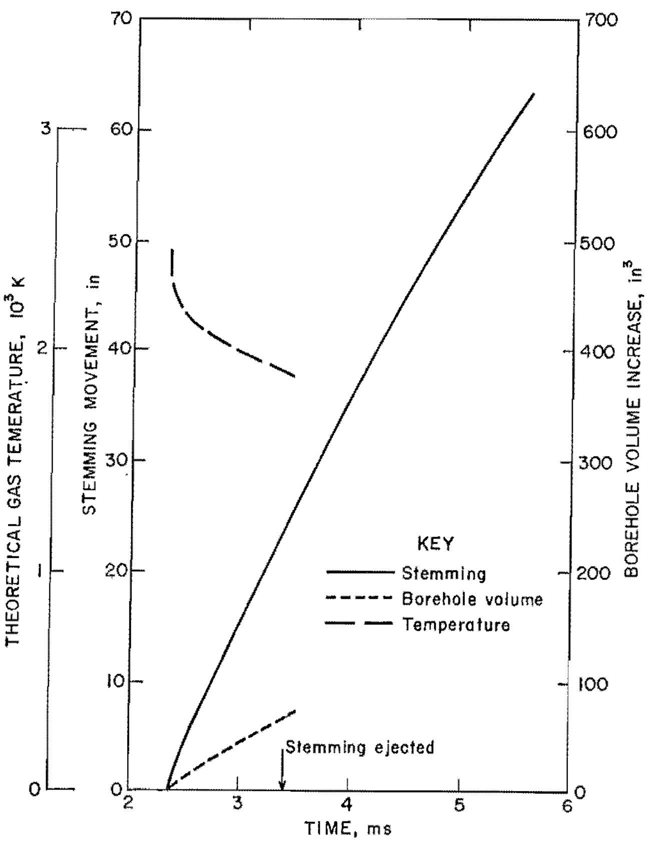

FIGURE 6.—Relative movements of stemming and burden for horizontal shot H-3 and associated explosive gas temperature.

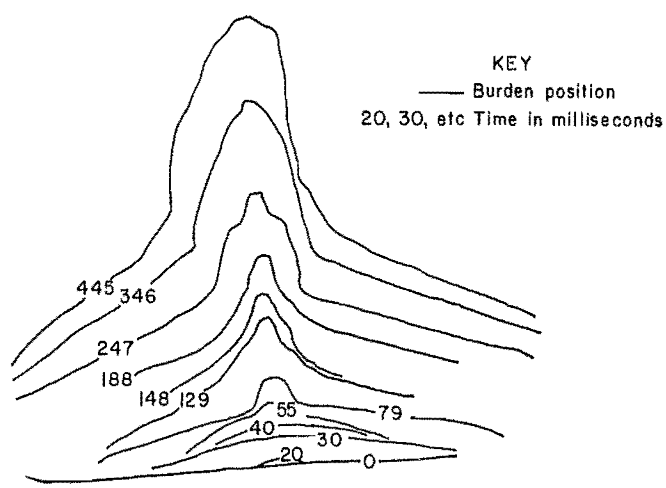

FIGURE 7.—Stemming and burden movements for shot V-1, a 6-in-diameter vertical blasthole.

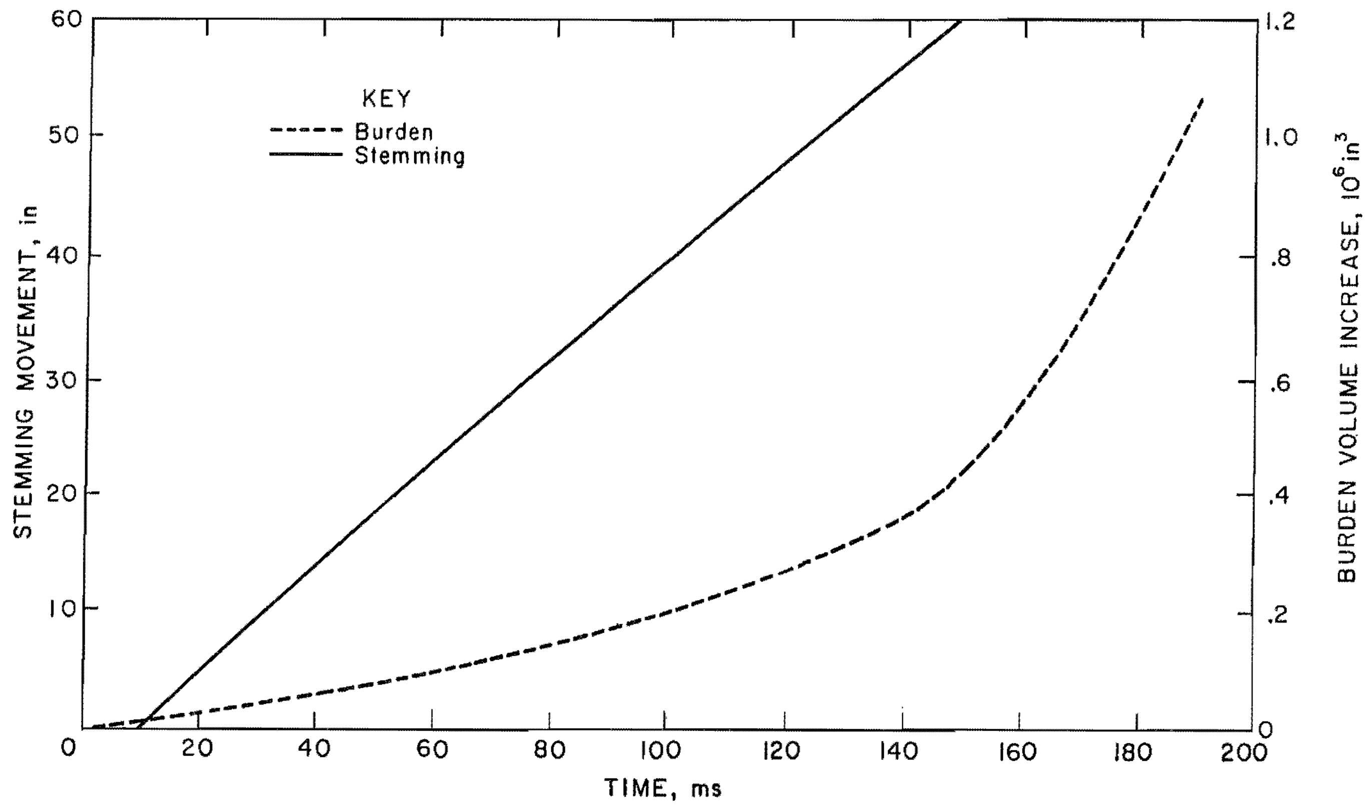

FIGURE 8.—Relative stemming and burden movements foı shot V-1.

A simple physical model has been suggested to predict the time required to eject stemming.[6] This model depends only on inertia of the stemming material and not frictional forces to resist movement and thus the acceleration, a, of the stemming is given by

$$a = \frac{F}{M}, \tag{4}$$

where F is the force exerted on the stemming by explosive gasses, and M is the mass of the stemming. The equation of motion is thus

$$S = V_o\, t + 1/2\, a\, t^2, \tag{5}$$

where S is distance traveled by the stemming, V_o is initial velocity, and t (time) is seconds. Combining equations 4 and 5 with $V_o = 0$ gives

$$t = \sqrt{\frac{2SM}{F}}. \tag{6}$$

[6]Work cited in footnote 2.

The force, F, can be estimated from the borehole pressure, P, times the cross sectional area of the hole, A, or

$$F = PA, \tag{7}$$

and the mass of stemming equals

$$M = \rho_s\, A\ell, \tag{8}$$

where ρ_s is the density of stemming material, A is the cross sectional area, and ℓ is the length of stemming. Substituting gives

$$t = \sqrt{\frac{2S\ \rho_s\ \ell}{P}}. \tag{9}$$

This prediction method yields ejection times for the shots in this investigation as shown in table 5. Also shown in table 5 is the time of first observed stemming movement and observed time to ejection.

All observed times for ejection were much longer than the calculated time. In all cases, no stemming movement was observed before the calculated time was past. This method then should only be

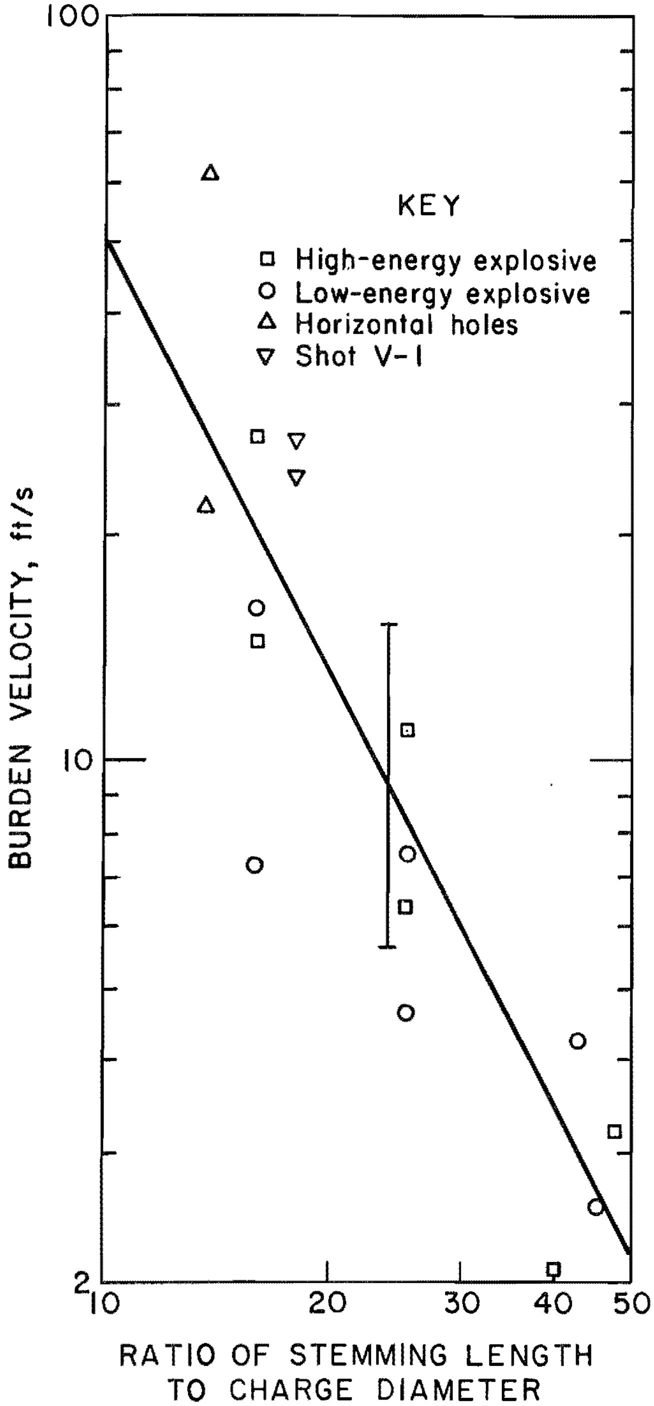

FIGURE 9.—Burden velocity versus scaled stemming length.

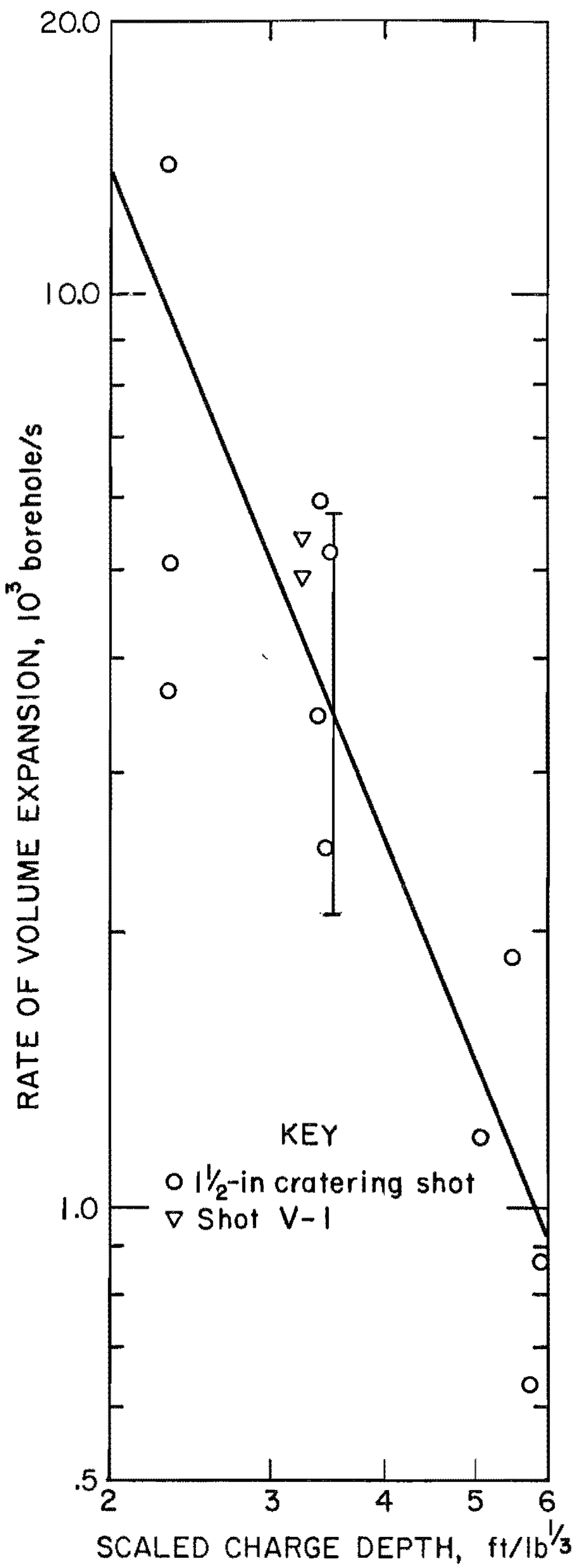

FIGURE 10.—Rate of burden increase versus scaled charge depth.

used to obtain an estimate of the minimum stemming ejection time. Improved estimates will require the addition of frictional forces.

A clue to this late stemming movement is also provided by the instrumentation used in shot V-1. These blastholes were instrumented with the SLIFER system to monitor the detonation rate of the explosive. This instrument also observed the rate of crushing or compaction of the stemming in the borehole. The record for hole 3 of shot V-1 is shown in figure 11. The first 6 ft of the record shows the detonation of the explosive. The detonation velocity is approximately 19,000 ft/s. Above 6 ft, the record shows the crushing of the stemming. This crushing extends to 12-1/2 ft from the bottom of the hole, or 6-1/2 ft of stemming, and takes 7.5 ms to complete. The crushing rate rapidly falls from near the detonation velocity of the explosive to a value below the stress wave velocity and then drops to 0 as shown in figure 12. The time taken for the crushing to propogate through the stemming (7.5 ms) is close to but somewhat less than the observed time for the start of stemming movement (10 ms). The stemming appears to be bridging in the hole and preventing movement until it is crushed by the pressure pulse in the stemming column and only then does it start to move.

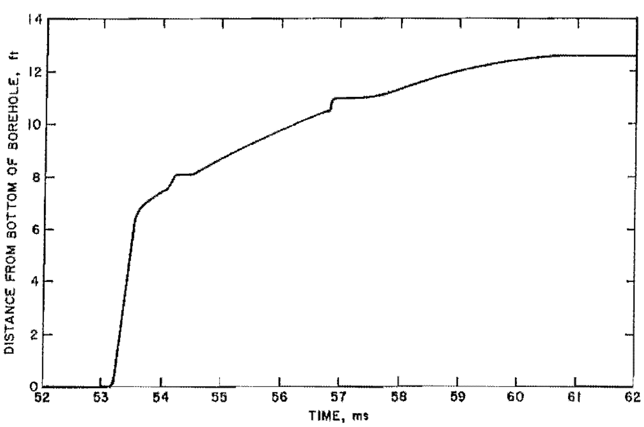

FIGURE 11.—SLIFER data from hole 3 of shot V-1 showing detonation of the explosive column and the crushing rate of the stemming. (From Sandia National Laboratories.)

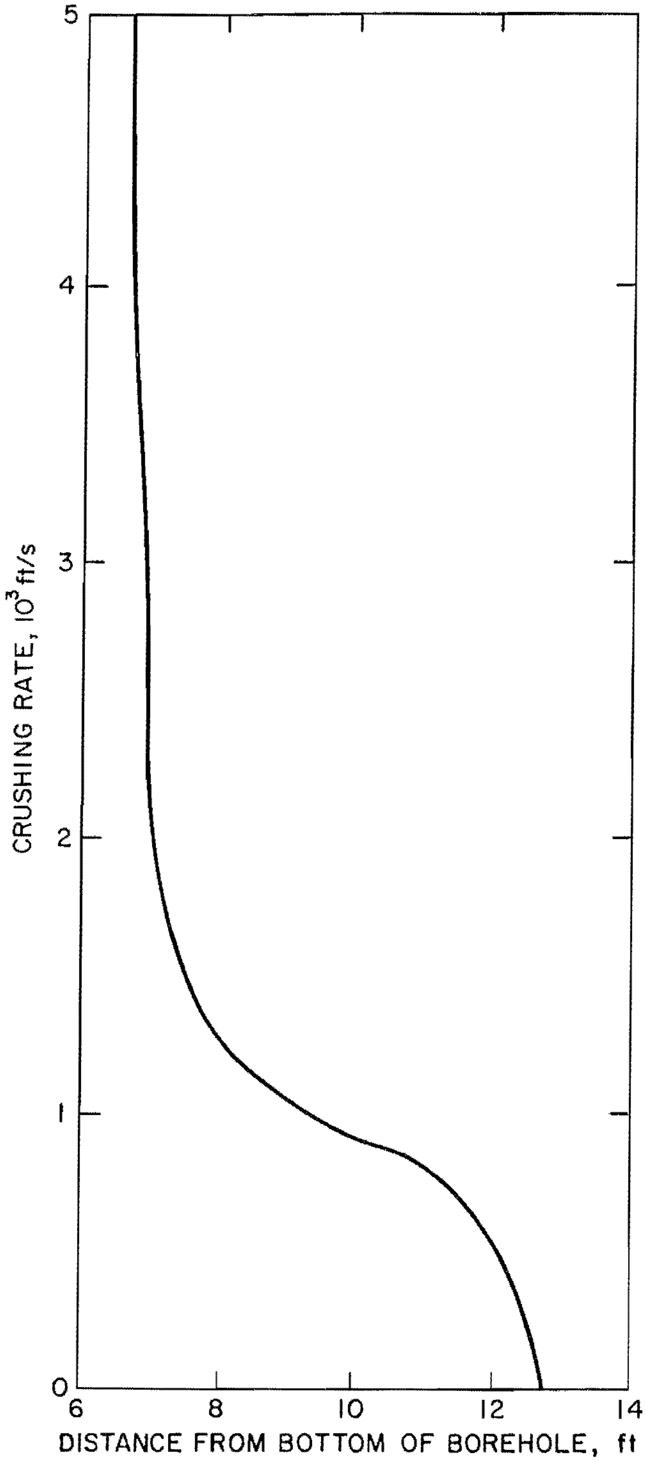

FIGURE 12.—SLIFER data from figure 11 replotted to show crushing rate in stemming region.

TABLE 5. - Calculated and observed stemming ejection times

Shot	Hole diameter, in	Stemming length, in	Ejection time, ms		1st stemming movement, ms
			Calculated	Observed	
S-3....................	1-1/2	20	0.5	13	3.4
S-4....................	1-1/2	20	.5	9	4.6
S-6....................	1-1/2	20	.6	32	6.1
H-1....................	1-7/8	24	.5	4	2.2
H-2....................	1-7/8	24	.5	4	2.0
H-3....................	1-7/8	24	.5	4	2.4
V-1[1]....................	6	108	2.1	Retained	10

[1]Hole 3 only.

CONCLUSIONS

High-speed films of single-hole crater test blasts in two surface limestone quarries were analyzed to evaluate the ability of stemming to contain explosive gases, which have the potential to ignite methane and dust explosions in underground mines. Stemming ejection and burden motions were examined. When sufficient stemming was used, ejection of stemming was prevented. A length of stemming to charge diameter ratio of 26 or more was found to prevent premature ejection of stemming, and venting of gases.

If release of stemming does occur, the time required for stemming ejection may be sufficient to permit burden movement to start with expansion of explosive gases into the fractured burden and the associated cooling of the explosive gases. An estimate of this cooling was made using thermodynamic principles. In three tests with a stemming length to charge diameter ratio of 16, the explosive gases would have cooled below the ignition temperature of methane (905 K) in the time required for stemming ejection but venting of gases through fractures occurred before stemming ejection and the temperature of the vented gas was estimated to be above the methane ignition temperature. For the conditions of these tests, it is thus concluded that a stemming length of 16 charge diameters could have resulted in methane ignition.

The burden movement could be scaled to account for different borehole diameters by use of either a simple ratio of stemming length to charge diameter or the scaled depth of burial. The scaled depth of burial was found by the formula

$$SD = d/\sqrt[3]{W},$$

where SD is scaled depth of burial; d is the depth to the center of the top of the explosive charge, in feet; and W is the weight, in pounds, of explosive in the top eight borehole diameters of the loaded blasthole. Burden movements correlated with both of these scale factors but burden velocities scaled better using the stemming length to the charge diameter ratio, and total burden expansion correlated best using scaled depth of burial.

Stemming ejection takes much longer and is more complex than a simple calculation, based on inertia of the stemming material, would predict. Reasons for this are the additional time required for the stress wave to crush the stemming material and cause it to start to move, and the subsequent decrease of borehole pressure through crushing and expansion of the borehole. A better understanding of these mechanisms requires further research with more sophisticated instrumentation, such as the Sandia shorted length indication by frequency of electrical resonance (SLIFER) system. Ejection times were three times or greater than those predicted by a simple inertia model.

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